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Tunable Phase Shifter Based on Few-Layer Graphene Flakes

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***Abstract*—This work presents a voltage-controlled tunable phase shifter based on few-layer graphene. The phase shifter consists of a stub-loaded line, composed of a microstrip line with a stub attached to it through a taper and graphene pad. The bias voltage applied to the graphene pad determines a variation of graphene resistance, which eventually causes the phase change. Without any voltage bias, graphene exhibits high resistance, thus isolating the stub and leading to a low phase shift. As the bias voltage is increased, graphene resistance is lowered, the effect of the stub is more pronounced, and the phase shift is increased. A prototype operating in the frequency range from 5 GHz to 6 GHz has been designed and tested. The measured maximum phase shift obtained is 40 deg and the corresponding degradation of the insertion loss is 3 dB.**

***Index Terms*—Few-layer graphene, graphene, phase shifter, tunable microwave devices.**

I. INTRODUCTION

THE USE OF GRAPHENE has gained significant interest in recent years for microwave applications [1], [2]. In this frequency range, the most important property of graphene is its change in resistivity upon application of a bias voltage [2]. This change in resistivity is electronically controlled and covers a quite wide range. In microwave applications, large areas of graphene are required. For this reason, few-layer graphene flakes are usually preferred [3], [4], which are easier to fabricate than mono-layer graphene, while preserving comparable tunable resistive properties [5], [6].

The tunable behavior of graphene has been exploited in the implementation of tunable attenuators [4] and antennas [7], besides many other interesting microwave components [2]. The use of graphene in phase shifters has been proposed for realizing diodes, which provide nonlinear behavior and lead to a phase shift [9]. The process of fabricating graphene-based diodes to obtain phase shifter is technologically demanding since it requires monolayer graphene deposited on nanomaterials.

This paper proposes a very simple way to obtain a phase shift equivalent to graphene-diode based devices, with the use of the easier technology of few-layer graphene flakes. The proposed structure is a stub-loaded line phase shifter, composed of a 50-Ω microstrip line with a shorted stub attached to it (Fig. 1). A tapered structure at the stub input is used for matching purposes. A graphene pad is deployed in the gap of the microstrip stub, to mimic reactive change as in diodes. The structure is optimized so as to get a maximum change in the reactive part of the stub input impedance when varying the graphene resistance.

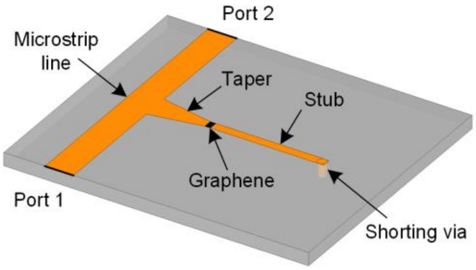

Fig 1. Geometry of the graphene-based tunable phase shifter.

The design of the phase shifter is discussed in this letter, along with its experimental validation. The phase shifter has been optimized in the frequency range from 5 GHz to 6 GHz, to provide maximum phase shift and minimum insertion loss.

II. DESIGN OF THE TUNABLE PHASE SHIFTER

The proposed topology of the tunable phase shifter is shown in Fig. 1, whereas the geometry of the stub is detailed in Fig. 2, along with its equivalent circuit. The phase shifter was implemented on a Taconic RF-35 substrate with a thickness of 1.52 mm. The relative dielectric permittivity of the substrate is $\varepsilon_r = 3.5$ and the loss tangent is $\tan\delta = 0.0018$. The width of the main microstrip line is 3.26 mm to ensure a 50 Ω line. The width of the stub is 1 mm, which corresponds to a characteristic impedance of 100 Ω. The graphene pad has a length of g=0.66 mm and width equal to the width of the stub.

The stub has been designed along the lines of [7]: the geometrical dimensions have been optimized for maximum phase shift and minimum insertion loss in the transmission from port 1 to port 2, when there is a change in the resistance R of graphene. The lengths L_1 of the stub and L_2 of the tapered line have been selected on the basis of two requirements: to maximize the variation in the input reactance $\mathrm{Im}\{Z_{in}\}$ and to minimize the variation in the input resistance $\mathrm{Re}\{Z_{in}\}$, versus the graphene resistance.

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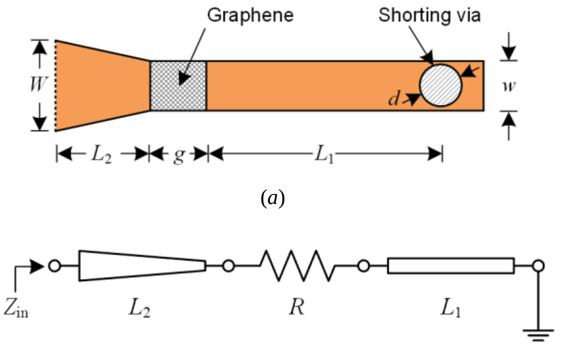


(*a*)

(*b*)

Fig. 2. Detail of the microstrip stub integrated with the graphene pad: (*a*) Geometry of the stub (dimensions in mm: L_1=12, L_2=6, g=0.66, d=0.8, w=1, W=3.26); (*b*) Equivalent circuit.

A systematic study based on simulations with the commercial FEM solver HFSS has been performed for the various lengths. Few-layer graphene flakes can be modeled at microwave frequency as an infinitely thin resistive sheet, as widely discussed in [2], [4]. Simulations have been performed for a graphene resistance R ranging from 0 to 1500 Ω. The results of this study are shown in Fig. 3. The optimum values result L_1=12 mm and L_2=6 mm, which provide the best compromise between the two requirements.

By using the dimensions obtained from the optimization of the stub, the entire phase shifter has been simulated in the frequency band of 5 GHz to 6 GHz by using HFSS. As expected, there was a phase shift of approximately 40 deg, with an increase in transmission loss up to 4 dB as shown in the Figs. 4*a* and 4*b*.

III. PROTOTYPE AND EXPERIMENTAL VALIDATION

A prototype of the tunable phase shifter was fabricated by using an LPKF micro-milling machine. The shorting via at the end of the stub was filled with conductive paste. The last step of the fabrication was the deposition of the graphene flakes, obtained by microwave exfoliation [4]-[7].

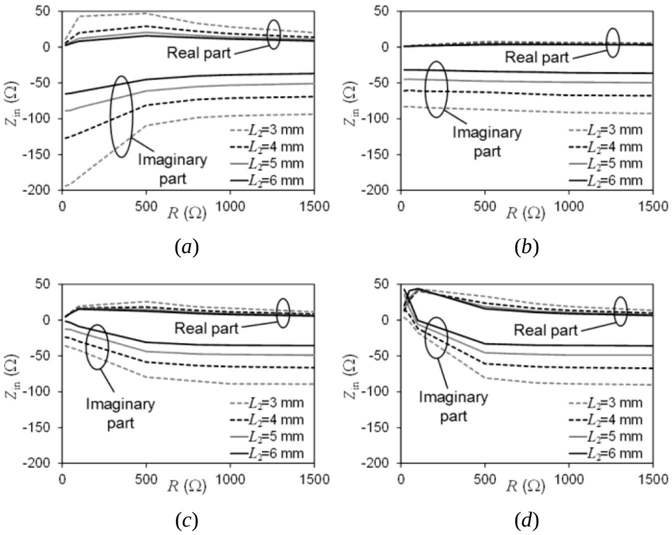
The prototype was tested by adopting the measurement setup shown in the Fig. 5, with biasing performed by using a bias tee. The bias voltage applied through the bias tee was set between the microstrip line and the ground plane, since the stub is grounded.

As a first step, the graphene DC resistance versus applied bias voltage was measured, and the graphene resistance R was calculated as the ratio between applied voltage and the current flowing through the phase shifter ($R=V_{\text{bias}}/I_{\text{dc}}$). The R-V_{bias} characteristic is reported in the Table I. The measured graphene resistance decreases when increasing the bias voltage. In the absence of bias voltage, the resistance of the graphene pad is R=1150 Ω, and it reaches the minimum value R=78 Ω for an applied voltage of 5 V.

TABLE I – GRAPHENE RESISTANCE VERSUS VOLTAGE

V_{bias} (V)	I_{dc} (A)	R (Ω)
0	===	1150*
3.5	0.0074	473
4	0.0157	255
5	0.064	78

* Measured by using a multimeter.



(*a*) (*b*)

(*c*) (*d*)

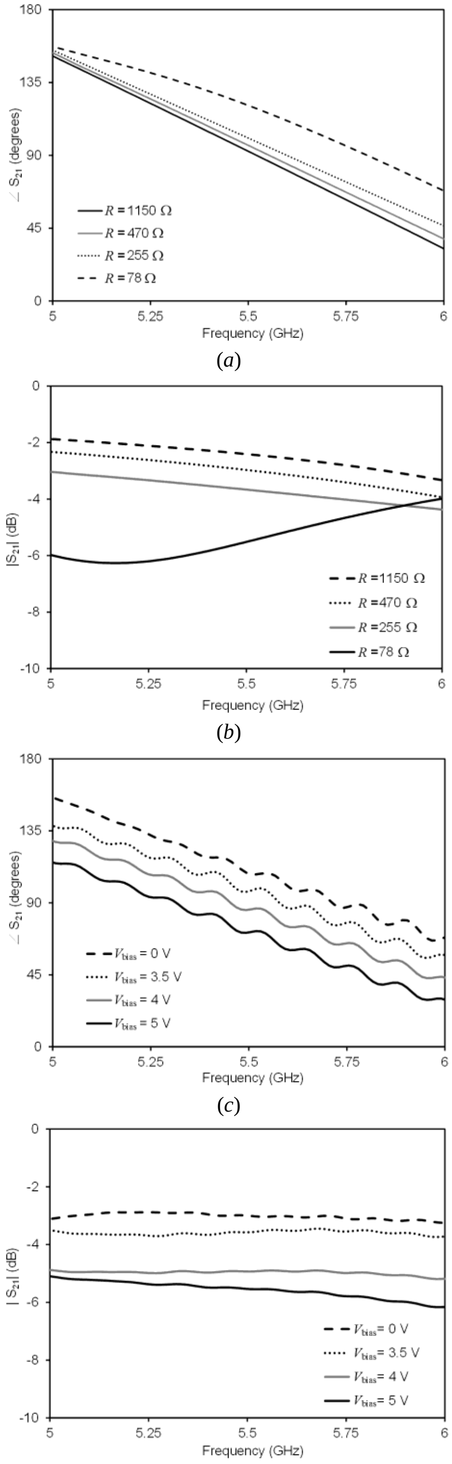
Fig. 3. Real and imaginary part of Z_{in} versus the graphene resistance for different values of the stub length L_1 and the taper length L_2, at the frequency of 5 GHz: (*a*) L_1=6 mm; (*b*) L_1=9 mm; (*c*) L_1=12 mm; (*d*) L_1=15 mm.

As a second step, the values of the scattering parameters were measured for each value of the applied bias voltage in the frequency range from 5 GHz to 6 GHz by using a vector network analyzer. The network analyzer had been calibrated with the reference ports defined as shown in the Fig. 5, in order to include the bias tee and remove their effects. The measured scattering parameters of the phase shifter are shown in Figs. 4*c* and 4*d*. To be able to compare simulations and measurements, the values of graphene resistance adopted in the simulations (Figs. 4*a* and 4*b*) correspond to the measured resistance for the values of bias voltage applied in the measurements (Figs. 4*c* and 4*d*), according to Table I.

The measured phase shift ranges from 35 deg to 43 deg over the entire frequency range. The measured insertion loss varies from 2 dB to 3 dB (when V_{bias}=0) to 5 dB to 6 dB (when V_{bias}=5 V), with a maximum degradation of 3 dB.

A comparison of the proposed phase shift with other structures presented in literature [8], [9] is shown in the Table II. The graphene phase shifter presented here ensures maximum phase shift with minimum insertion loss among the other nanomaterial-based phase shifters.

Conventionally, ferroelectric varactors-based phase shifters are widely used accompanied by transmission line circuitry as shown in [10]. Compared to graphene phase shifters, varactors-based phase shifters are more power hungry and needs voltages of the order of 100 V. For the sake of comparison at a bias voltage of 5 V the phase shift acquired by commercially available varactor diodes is only 20 deg as shown in [11]. Furthermore, they are bulky and have to be surface mounted while the tunable resistance of graphene flakes can be exploited even at a nanometric scale keeping constant aspect ratio. Solutions based on thin-film technology [12] are less bulky, at the cost of narrow band performance.



(*a*)

(*b*)

(*c*)

(*d*)

Fig. 4. Simulated and measured scattering parameters of the phase shifter: (*a*) Simulated phase of S_{21}; (*b*) Simulated amplitude of S_{21}; (*c*) Measured phase of S_{21}; (*d*) Measured amplitude of S_{21}.

IV. CONCLUSION

In this paper, a graphene-based phase shifter has been proposed, which consists of a shorted stub with a gap, where few-layer graphene flakes are deposited. When changing the bias voltage, the proposed device introduces a phase change of approximately 40 deg in the frequency range from 5 GHz to 6 GHz, at the cost of an additional loss of 3 dB.

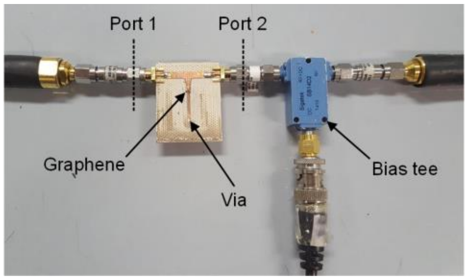


Fig. 5 Measurement setup of the tunable phase shifter, with position of the reference ports.

TABLE II – COMPARISON OF NANOMATERIAL-BASED PHASE SHIFTERS

	Graphene Schottkey [8]	HfO_2 [9]	BST Thick-Film [10]	BST Thin-Film [12]	This work
Insertion Loss (dB)	5-10	14-6	1.2	3.3	3
Frequency band (GHz)	40-65	1-10	2-3	9.75-10.25	5-6
Phase (deg)	20	30	70	97	35-43
FOM* (deg/dB)	6.5	1.67	58.2	29	14.3
Maximum Voltage (V)	5	3	100	400	5

* FOM represents the figure of merit, defined as the ratio of the maximum differential phase shift and the insertion loss at the same frequency.

The use of graphene open a new paradigm for phase shifters. In fact, ferrites are heavy, expensive and technologically highly demanding, and semiconductors are also technologically demanding and require large control voltage. Conversely, the proposed solution presents several advantages compared to traditional technologies: it is easy to realize, compact, low cost, and requires low control voltage.

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